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Assessment of Progressive Damages in Concrete with Acoustic Emission Technique

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Abstract

This research describes an experimental study in which acoustic emission (AE) technique was applied for evaluating damages in concrete. Standard size cubic (150x150x150mm) and cylindrical (100x200mm) specimens were produced with three different w/c. The cylindrical specimens were tested to measure the concrete compressive strength. The cubic specimens were subjected to various loading and unloading cycles while the acoustic emission evaluation was performed with AE sensors to listen to the wide range of events. For assessing concrete deterioration the occurrence of Kaiser and Felicity effects at each loading and unloading stage were carefully examined. It was observed that AE hits increases as damage increases. Additionally, normalized values of Felicity ratio were plotted in order to examine any correlation between the acoustic emission technique and the applied load for assessment of damage growth in concrete. The influence of w/c on sensitivity of the AE technique in detecting concrete damages was also investigated.

Keywords

Acoustic Emission; Compressive; Damage; Felicity Ratio; Kasier Effect

Introduction

Damage in concrete members can be of many levels leading from micro-cracking to large fractures. Concrete members are generally cracked even when no load is applied to them. Therefore, regular inspection of existing and aging structures is very essential for quantifying the condition of structural integrity and assessing the degree of damage and deterioration [1]. Additionally, it is important to detect cracks at a very early stage or, even better, to detect changes in the microstructure before the crack initiation even occurs. For this purpose the inspection methods that can be used to provide early detection and warning for critical defects are in great demands [2].

Acoustic emission (AE) technique is an experimental tool that is well suited for monitoring fatigue and fracture behaviors [3–7]. Hence it is effective for detecting actual damage in structures. AE failed to show substantial changes in terms of the number of AE events or the scale of amplitude. However, improved b-value, described below, demonstrated the possibility to quantify the damage [6]. The AE technique has two areas of broad applications: it is used for nondestructive evaluation and it is also a tool in studies that are not fundamentally directed toward acoustic emission [8, 9].

As concrete is a heterogeneous material, consisting of different phases, the inelastic zone around a crack tip is termed a fracture process zone behavior of the fracture process zone in concrete was investigated experimentally with X-rays using contrast medium and three-dimensional (3D) AE techniques [10]. It was shown that, as the loading increases, a zone consisting of numerous micro-cracks, accompanied by AE events, develops ahead of the notch tip in the concrete compact tension specimen.

Relation of fracture process zone to tension softening behaviour of concrete has been studied using an AE source location technique and simulation of tension softening behavior in double cantilever beam specimens [11]. The results indicated that the beginning of descending branch in tension softening diagram corresponds to micro-crack localization and extension and that the tail of tension softening is

attributed to the bridging mechanism at the interface between the matrix and aggregates. In another study an AE examination technique was used to determine the dimensions of the micro-cracked zone leading a macro-crack propagating in concrete [12].

Localization of micro-cracks in unnotched concrete specimens under axial tension was studied using AE analysis techniques [13]. It was found that the AE events started to concentrate on a narrow band of the specimen when the load reached about 80% of the peak value. Based on the experimental observations, it was found that the localization of micro-cracks controlled the development of the macro-crack in the specimen.

Concrete structures contain flaws, such as pores, air voids, and shrinkage cracks even before they are mechanically loaded. These flaws cause micro-cracks under the external loading, which extend to macro-cracks until large fractures are formed, yielding collapse of the structure. To describe the fracture mechanism as well as fracture parameters and to locate cracks AE has been used. Models of crack initiation and subcritical growth in quasi-brittle materials were elaborated while the non-stationary dynamic problems of the crack theory were formulated [14]. A variety of new analytical relationships between crack parameters and AE signal parameters suitable for engineering calculations was obtained.

Applications of nondestructive and noninvasive diagnostic methods such as interferometry and acoustic techniques to cementitious materials were studied [15]. It was demonstrated that these techniques are pertinent to issues like growth and propagation of micro-cracks under service loads and could evolve into effective on-site monitoring tools [16, 17]. Further, a three-dimensional (3D) AE has been applied to observe the phase of the fracture zone of concrete ahead of the crack tip, which significantly affects the tension softening behavior of concrete [18]. It was revealed that the fracture process zone may expand as the crack grows and the expanding rate of the process zone is influenced by the aggregate size.

Applicability of Kaiser effect for assessing the deterioration of concrete structures was suggested [19]. This effect is an AE phenomenon, briefly defined as the absence of detectable acoustic emissions until the previously applied stress level is exceeded. The discovery of Kaiser effect offers an alternative method to understand the stress history and estimate the damage of material in structures.

b-value analysis of AE signals was used to assess the damage that occurred in reinforced concrete beams [20]. b-value is derived from the amplitude distribution data of AE following the methods used in seismology. The b-value is defined as the 'log-linear slope of the frequency magnitude distribution' of AE. It represents the 'scaling of magnitude distribution' of AE, and is a measure of the relative numbers of small and large AE which are signatures of localized failures in materials under stress. A high b-value arises due to a large number of small AE hits (or events) representing new crack formation and slow crack growth, whereas a low b-value indicates faster or unstable crack growth accompanied by relatively high amplitude AE in large numbers. Thus b-value is very useful in making a quantitative diagnosis of the fracture development in the test solid or structure under stress based on AE amplitude information.

AE was used to quantify damage in generic laboratory structures for tuning damage models [21]. It was demonstrated that there is a correlation between the fracture energy and AE energy for fine-grained specimens. However the relationship obtained was not as good for coarse-grained specimens. Toughening mechanisms such as friction were suggested as being responsible for the poor relationship observed in the coarse-grained materials. It was further suggested that AE energy release can be related to actual crack formation energy but not to friction and other internal energy dissipation or toughening mechanisms.

Damage estimation of structural concrete from concrete samples was developed, combining acoustic emission damage measurements with mechanics [22]. AE characteristics due to microcracking were studied in full scale pre-stressed concrete piles under both cyclic and monotonic loads [23]. It was shown that in heavily damaged piles due to bending, rough evaluation of the integrity is possible by pile integrity test (PIT), whereas precise estimation of crack location is not easy.

Pile integrity is possibly evaluated by examining AE activity by direct monitoring based on the Kaiser effect. The secondary AE activity is strongly dependent on the inclination of crack rather than the crack width. Acoustic emission characteristics of threepoint bending concrete beams were investigated during the entire loading period and found that relative notch depth significantly influenced AE

characteristics [24].

The goal of the present experimental study is to examine the correlation between the AE technique and damage. Sensitivity of AE test method in detecting cracks or defects is certainly influenced by the micro-structural behavior, which in turn is influenced by the change in damage level and w/c. It is, therefore, appropriate to find a relationship between the AE technique and damage growth in concrete. The outcomes of this research will bring an easy understanding of concrete material behavior under axial compression loading. It will be very useful in applying successful structural health monitoring, repair, and rehabilitation activities.

Experimental

Eighteen cubic (150x150x150mm) and nine cylindrical (100x200mm) specimens were produced from three batches of concrete using w/c of 0.40, 0.50, and 0.60. Each w/c consisted of six cubic and three cylindrical specimens. The cylinders were tested to measure the ultimate concrete compressive strength. The obtained compressive strength was used to estimate the ultimate strength of the cubes, which was applied as load in several steps using percent of ultimate strength simaltenously with AE evaluation.The mean value of the three test specimens was used for analysis and comparison of the test results. The concrete material properties and mix proportion are tabulated in Tables 1 and 2.

TABLE 1 MATERIAL PROPERTIES

Materials	Density (gm/cm³)
Normal Portland Cement	3.16
Sand	2.62; Absorption: 1.50%
Crushed Stones	2.62; Absorption: 0.65%; Maximum Aaggregate Size: 12 mm

TABLE 2 MIX PROPORTIONS

W/C	Cement (Kg/m³)	Water (Kg/m³)	Sand (Kg/m³)	Crushed Stones (Kg/m³)	AEA* (Kg/m³)	WRA** (Kg/m³)	Slump (cm)
0.40	425	170	786	917	2.13	1.28	8.0
0.50	340	170	858	917	1.70	0.85	10.0
0.60	284	170	905	917	1.42	0.55	10.50

Note: *AEA: Air Entrainging Agent; **WRA: Water Reducing Agent.

Fig. 1 shows the test setup for AE experiments. The test setup is composed of AE sensors of R15 type [7] with resonance frequency of 50–200 kHz. They were connected to pre-amplifiers of 1220A type and were firmly fixed at the center of the cube surfaces with special wax couplant and rubber bands. Additionally, an AE monitoring system, a Universal Testing Machine (UTM), an agilant, an oscilloscope and a PC were also attached. AE events, induced by compression loading, were subsequently amplified by 45 dB at preamplifiers and fed in AE monitoring system. Both AE parameters and waveforms were recorded with the system.

The AE tests were performed on specimens that were subjected to cyclic compression loading in several steps. At each step AE activities were recorded both during loading and unloading operations. Fig. 2 shows a schematic view of the occurrence of AE activity under incremental cyclic loads with four different levels of damage i.e., in-tact; almost in-tact; slightly damaged and heavily damaged.

In the second cyclic load, AE activity would start to be observed at the maximum prior load level, which is called as Kaiser effect [19]. At third cyclic load, the onset of AE appearance would be at a load level lower than previously applied. Felicity ratio (load ratio) [26–28] was used in order to express the relationship between the AE activity and the stress level experienced. Similarly, with the evolution of damage, not only the AE activity during uploading, but that during unloading operation was also considered very important [23]. This phenomenon is referred to as Calm ratio [28].

In this research, Felicity ratio was used as a reliable measure of AE evaluation of compression induced damages in concrete. It is defined as the load where considerable AE resumes, divided by the maximum applied load. Since, concrete contains defects even at early loading stages it was hard to clearly locate the onset, at which AE activity resumes. Felicity ratio was, therefore, measured during reloading operation for the load levels, corresponding to AE hits at 3%, 5%, and 10%, respectively, of the AE hits at the previous maximum load. The idea was in fact to use Felicity ratio as a measure of damage assessment with different sensitivity levels to detecting damages in concrete. Normalized values of the measured Felicity ratio at three different points were, therefore, plotted and compared with the change in damage or loading level. Sensitivity of the method to assessing damage growth in concrete with different w/c was also examined.

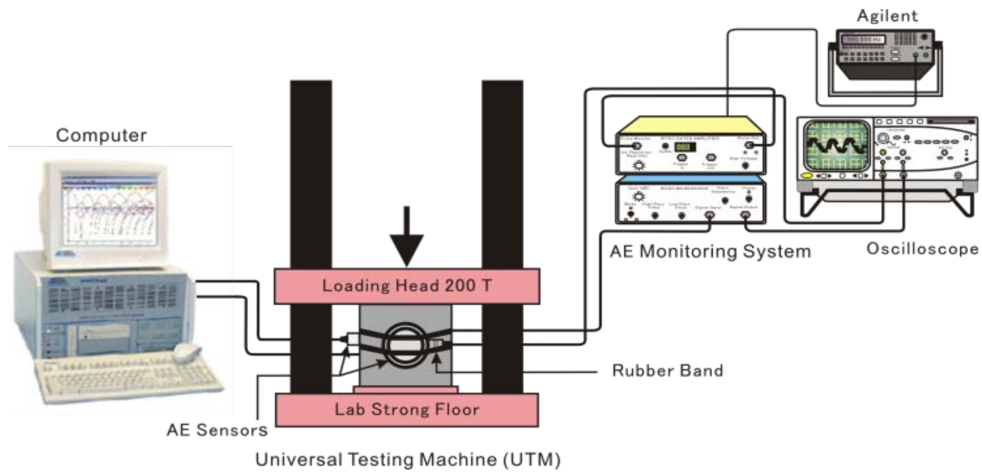

FIG. 1 TEST SETUP

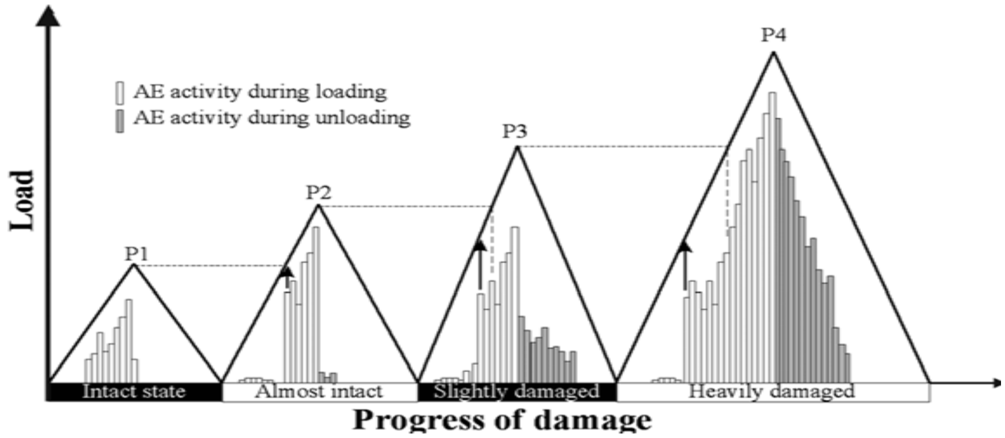

FIG. 2 SCHEMACTIC VIEW OF AE ACTIVITY WITH DAMAGE [25]

Discussion of Test Results

This research was aimed at investigating a relationship between the AE parameter and the applied load or damage as percent of ultimate strength. Fig. 3 shows the mean test values of three specimens with w/c of 0.40, obtained using AE technique, under axial loading and unloading.

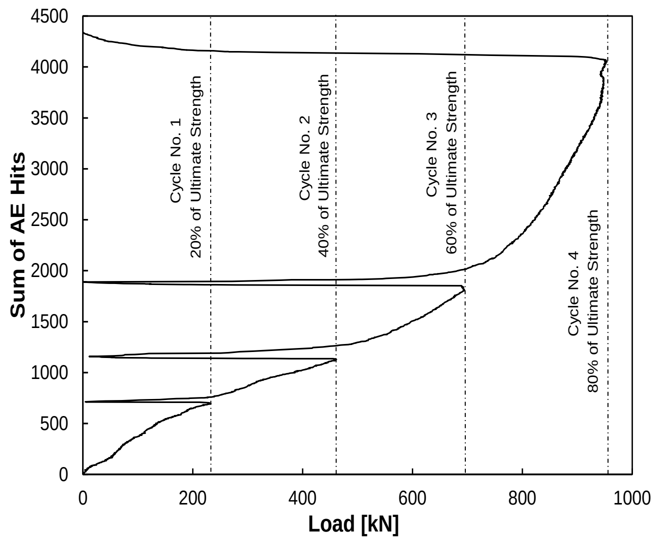

FIG. 3 SUM OF AE HITS WITH CHANGE IN LOAD FOR W/C=0.40

The test results have shown that AE activity increases as load increases. The AE hits rate shows the rate of total AE hits, derived from all AE channels. During several loading and unloading cycles the data obtained was thoroughly examined for the occurrence of Kaiser effect and other damage indices (Felicity ratio in particular). None of the specimens clearly exhibited any sign of perfect Kaisar effect occurrence. AE hits were actively generated during 30–40% of the previous maximum load even at the first cyclic loading stage. This suggests, as was seen previously [6, 22, 23] that Kaiser effect started to break from approximately 40% of the first maximum cyclic loading stage and continuous AE activity was obtained not only in loading, but also in unloading operation at below 40% of the previous maximum load at higher loading stages.

Additionally, each loading stage, where the AE activity resumes and the maximum applied load for calculating the Felicity ratio (wherever applicable), was carefully checked for the difference in load. Concrete is nonlinear in the shape of micro-cracks even before the application of load or at initial loading

stages [3–5, 7, 8]. Hence, as stated earlier, Felicity ratio was calculated by measuring the load readings at three different points, where the AE activity during reloading is supposed to resume i.e. 3%, 5%, and 10% of the AE hits at the previous maximum load, divided by the previous maximum load. By doing so Felicity ratio values, exhibiting both conservative and non-conservative trends towards damage assessment in concrete, were obtained.

Figs. 4 and 5 show similar characteristics, like those, presented in Fig. 3, for the test specimens with w/c of 0.50 and 0.60, respectively. Average results of three specimens using AE technique were plotted against the applied load.

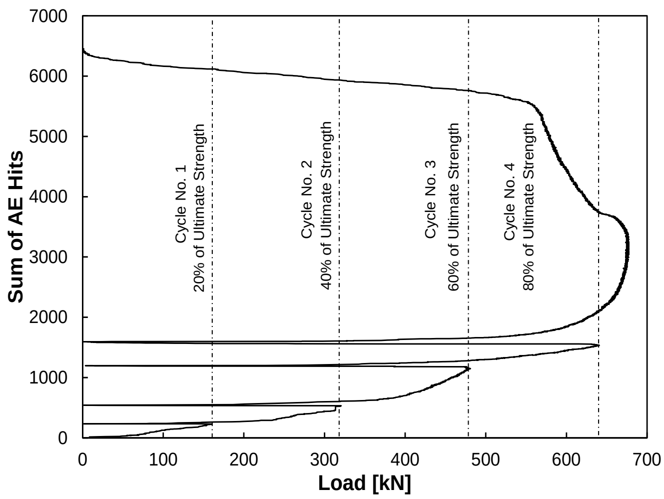

FIG. 4 SUM OF AE HITS WITH CHANGE IN LOAD FOR W/C=0.50

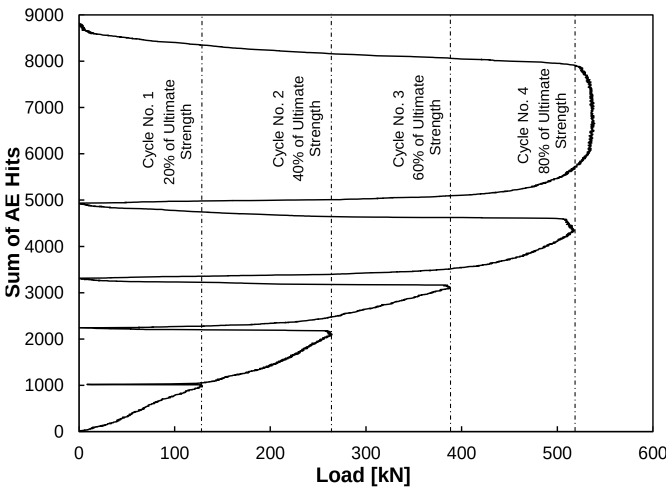

FIG. 5 SUM OF AE HITS WITH CHANGE IN LOAD FOR W/C=0.60

The trends of increasing AE events with damage are apparent in the figures. However, the increase in AE hits with damage for w/c of 0.50 and 0.60, respectively, is higher than that which occurred in the specimens with a w/c of 0.40. Like in Fig. 3, no sign of Kaiser effect was clearly observed. For both w/c concretes AE activity at each loading stage resumes at or below 30% of the previous maximum applied load. Hence, the loading points, yielding significant AE activities during reloading operations were carefully monitored. Felicity ratio was measured, as for 0.40 w/c concrete specimens, at three different reloading points, corresponding to the AE hits at 3%, 5%, and 10% of the AE events appeared at the previous maximum load.

Fig. 6 shows the normalized values of the Felicity ratio (FR) for w/c of 0.40 with progress in damage. A closed relationship between the two parameters in detecting concrete damages has been observed. Felicity ratio (FR), obtained at all three loading points during reloading operation, was reduced smoothly from the undamaged state as damage progressed. The FR value at 20% damage level indicates that even at early loading stages the occurrence of Kaiser effect was hard to observe.

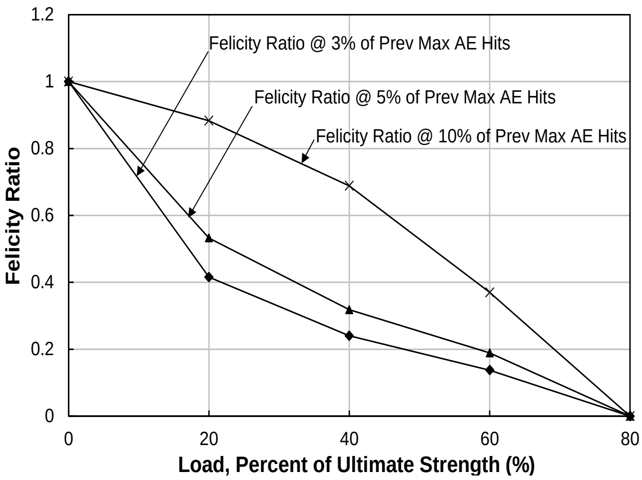

FIG. 6 AE PARAMETER VS THE APPLIED LOAD FOR W/C=0.40

It demonstrates that microcracking exists in this concrete under initial load application, due to which AE activity resumed at the load much less than the previous maximum load. Additionally, for these specimens AE results seem more sensitive to concrete damages for 3% and 5% than 10% of the AE hits at the previous maximum load.

Figs. 7 and 8 show the same information, like Fig. 6 for test specimens with w/c of 0.50 and 0.60, respectively. FR values were found decreasing with increasing damage. However, the reduction in FR for w/c of 0.50 and 0.60, with damage is greater than that obtained in specimens with w/c of 0.40. This is due to the fact that high w/c concrete in the undamaged state has more defects in the form of voids and porosity as well as a weaker interfacial transition zone than low w/c concrete has. These defects lead to premature micro-crack formation and higher reduction in FR or increased sensitivity of FR to detecting concrete

defects. Following the conservative trend (@ 3% and 5% of AE hits) in measuring the FR, the AE monitoring for these specimens has shown increased sensitivity to concrete damages.

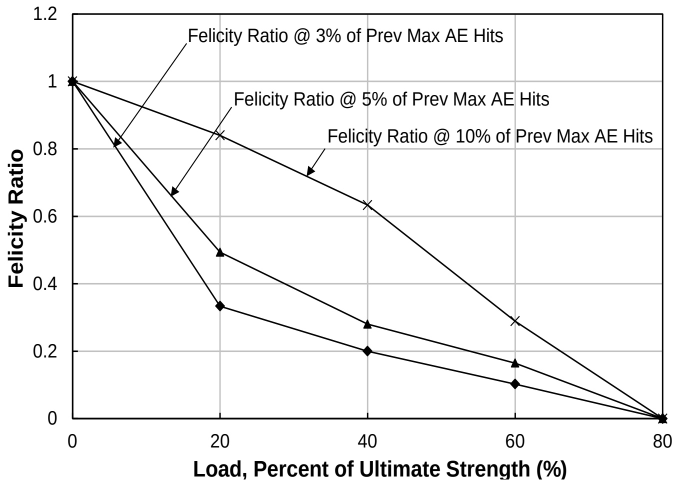

FIG. 7 AE PARAMETER VS THE APPLIED LOAD FOR W/C=0.50

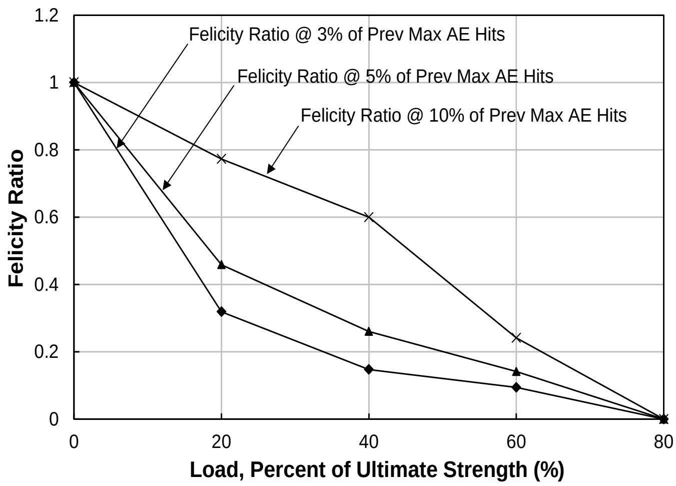

FIG. 8 AE PARAMETER VS THE APPLIED LOAD FOR W/C=0.60

The data plotted in Figs. 6–8 show close correlation between the AE parameter and the progression in damage. The FR, plotted with 3% and 5% of the previous maximum AE events, exhibited conservative trend and has shown higher sensitivity of AE testing to damage detection in concrete. On the other hand, FR, measured with 10% of the AE hits of the previous maximum load, has shown a nonconservative trend towards detecting damages in concrete. Using, conservative or non-conservative trends, AE monitoring can effectively perform damage assessment in concrete. Additionally, it can be used as an easy and simple measure of damage growth in concrete.

Conclusions

Eighteen cubic specimens, 150x150x150mm, and nine cylindrical specimens, 100x200mm, were produced to investigate the suitability of acoustic emission (AE) technique in nondestructive evaluation of concrete with progressive damages. For casting these specimens three concrete batches (six cubes and three cylinders at each batch) with w/c of 0.40, 0.50, and 0.60 were prepared. The cylindrical specimens were used for measuring the ultimate compressive strength while the cubes were allocated for AE evaluation under various loading and unloading cycles. At each cyclic loading stage the specimen was carefully examined for Kaiser and Felicity effects in order to assess the concrete deterioration. Additionally, normalized values of Felicity ratio were plotted in order to examine any correlation between acoustic emission technique and the applied load for assessment of damage growth in concrete. The influence of w/c on sensitivity of the AE technique in detecting concrete damages was also investigated. The test results analysis and discussion led to the following conclusions:

1. None of the test specimens exhibited clear signs of the occurrence of Kaiser effect.
2. The AE activity was found quite sensitive to change in the applied loading events and w/c. AE events increase significantly as damage progresses.
3. The increase in AE events was higher for high w/c concrete compared to low w/c one.
4. A close correlation between AE parameter Felecity ratio (FR) and applied loading (as percent of ultimate strength) in detecting concrete damages was observed.
5. The FR was found changing from undamaged state even under initial loading stages. This shows the sensitivity of the AE parameter in detecting even early age concrete damages. Generally, FR reduces smoothly from the undamaged state to damaged state as damage progresses.
6. FR, measured at three different loading points, exhibited conservative and nonconservative trends towards damage assessment.
7. Following conservative trend the AE index has shown greater sensitivity to concrete damages. However, with non-conservative trend the AE sensitivity to damage detection in concrete was reduced.
8. Generally, AE parameter appears to be an easy measure of assessing damages in concrete.

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